# HAYWARD, CALAVERAS, AND MISSION FAULT SUBSURFACE SLIP FROM JOINT ANALYSIS OF MICROEARTHQUAKE RECURRENCE AND SPACE GEODESY

**Roland Bürgmann**, University of California, Berkeley
Department of Earth and Planetary Science
307 McCone Hall
Berkeley, CA 94720-4767
Telephone: (510) 643-9545; FAX (510) 643-9980; burgmann@seismo.berkeley.edu
URL:http://www.seismo.berkeley.edu/~burgmann

# Progress Report for FY 2003 Activities

## Investigations Undertaken

Hayward Fault GPS Data Collection. As part of our ongoing effort to monitor active deformation along the Hayward fault, we determine positions of over sixty benchmarks within ten kilometers of the fault (Figure 1). These measurements provide an unprecedented spatial resolution of GPS measurements about an active fault. The first surveys of most benchmarks were made in 1998, and our group has been returning each year to take new measurements. The data from these campaigns are integrated with other regional data, including existing continuous stations, data collected by the USGS and CalTrans, and ongoing U.C. Berkeley campaigns active on the Calaveras and San Andreas faults. Combined, these data sets provide a complete picture of the regional surface deformation, strain partitioning between the faults, and interseismic strain accumulation.

InSAR Analysis of Interseismic Deformation. The currently available ERS data set over the Bay area consists of 3 descending-orbit frames (roughly 100 x 100 km squares) and 2 ascending-orbit frames. Previously, we analyzed a subset of interferograms spanning the northern Hayward fault and performed a joint analysis of InSAR, creep, GPS, and repeating microearthquake data (Bürgmann et al., 2000). The analysis revealed a potentially unlocked northern Hayward fault segment whose surface creep rate is reduced primarily by the pinning effects of the locked 1868 earthquake source region to the south (below ~ 5 km) and the tip of the creeping Hayward fault just

offshore Point Pinole. We have now expanded our data set to > 200 interferograms over the region (Schmidt, 2002).

East Bay Faults Point Slip Rate Measurements from Earthquake Recurrence. This method has been developed in our research program using data from a borehole network at Parkfield along the San Andreas fault. Studies at very high resolution of microearthquakes since 1987 revealed a systematic organization in space and time, dominated by spatial clustering of nearly identical, regularly recurring microearthquakes ('characteristic events') on small (meters to 10s of meters) patches within the fault zone (Nadeau and McEvilly, 1997). Characteristic events have been identified on the Hayward fault as well as on the Calaveras and Mission faults. We use the empirically derived equation of Nadeau and McEvilly (1999) to relate magnitude and recurrence intervals of events within characteristically repeating earthquake (CRE) sequences to fault creep around the sequence location.

Inverting for Aseismic Slip Distribution Along the Hayward Fault. The aseismic slip-rate distribution at depth on the Hayward fault is calculated through the use of space-based technology, namely GPS and differential radar interferometry (InSAR), and fault creep rates (Schmidt, 2002; Schmidt and Bürgmann, 2002). Surface creep rates and point creep rates at depth determined from characteristic repeating microearthquake sequences are used as additional constraints in the geodetic inversion. The ability to derive point measurements of fault slip at depth can significantly sharpen the resolution of the spatial distribution and magnitude of aseismic slip along fault surfaces. Using a double-difference earthquake relocation program, we can resolve the seismic structure of the Hayward fault in greater detail, which provides important information about sub-surface fault geometry and the relative location of point slip rates with respect to each other along the fault plane. Our results provide detailed information on the magnitude of subsurface aseismic fault slip and its variation in space and time.

## Results

Hayward Fault GPS Data Collection. During this grant cycle, we collected GPS measurements from 41 benchmarks in the vicinity of the Hayward fault, most in urban settings that require an operator to be with the station during the entire period of data collection (lasting at least 8 hours). Many stations have been occupied more than once, resulting in over 100 days of total data collection. Previously, we processed GPS data in BERNESE 4.2 to compute tightly constrained regional solutions. In order to better integrate our campaign solutions with other data sets, we have reprocessed our entire data holdings and computing loosely constrained solutions with MIT's GAMIT/GLOBK processing software. The resulting velocity field (called BAVU 1.0, with velocities of ~180 sites in the Bay Area) show excellent agreement with our previous processing and with other existing data sets. For example, a comparison of surface creep rates measured using GPS during this project and triangulation work by Lienkaemper et al. (2001) show similar results, especially for stations where the two observations were collected during identical time periods.
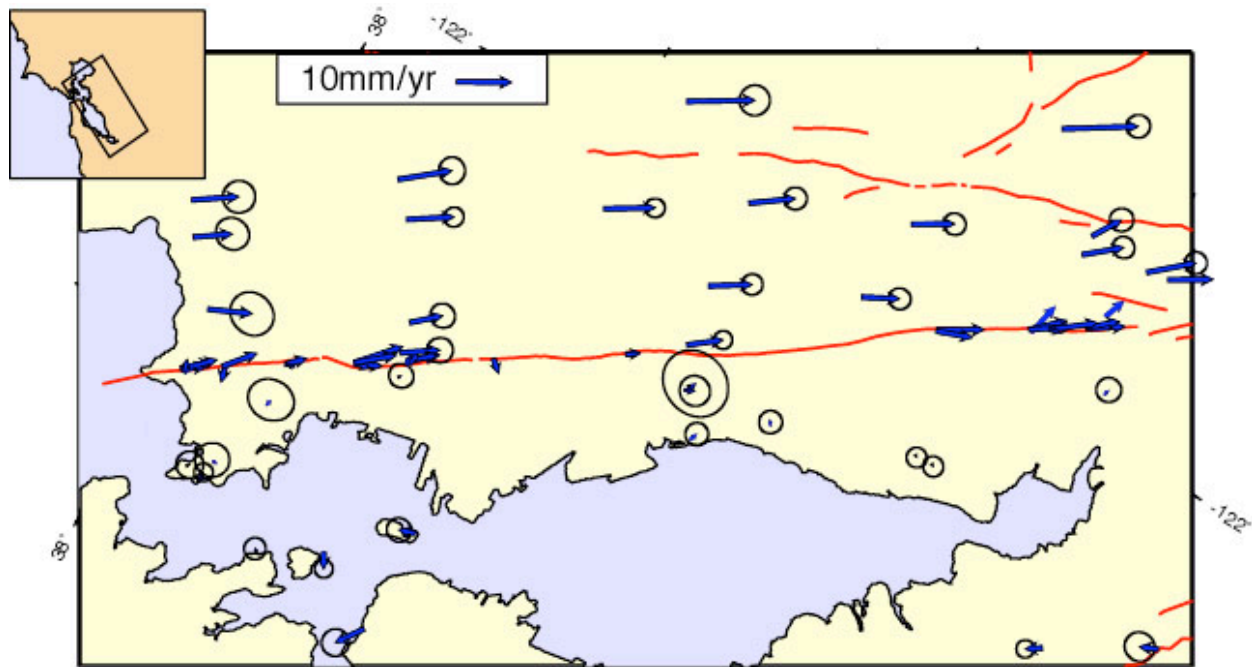
**Figure 1.** Map of GPS velocities along the Hayward fault for 1994-2003. Velocities are relative to continuous station LUTZ located on the Bay Block. The map is projected about the pole of rotation between the Pacific Plate and the Great Valley/Sierra Nevada block so that velocities along small circle paths show up as horizontal vectors.

InSAR Analysis of Interseismic Deformation. In the past year, we have begun the unprecedented formal integration of now almost 200 interferograms from 3 frames covering the central Bay area (Schmidt and Bürgmann, 2003). In this approach, data from all the interferograms are formally combined in a least-squares inversion to determine a time series of range change at each image element. This analysis can resolve transient deformation episodes, such as a large 1996 slip event on the southern Hayward fault (Schmidt et al., 2002).

As mentioned above, InSAR images of the Bay Area are primarily coherent over urban developed regions, whereas undeveloped regions that are vegetated and have steep topography are difficulty to use for interferometry spanning time intervals of greater than about 1 year. This includes terrain along portions of the Mission and Calaveras faults and along the San Andreas fault. We thus put a lot of effort into utilizing InSAR over areas with relatively scattered "islands of coherence". We are using both improved phase unwrapping algorithms (Chen and Zebker, 2001) and permanent scatterer techniques (Ferretti et al., 2000, 2001) to allow for the inclusion of data in these regions (Johansen and Bürgmann, 2001, 2002). This approach relies on methods to identify individual coherent pixels (such as buildings or outcrops) in an otherwise incoherent region. Figure 2 shows a stack of 8 1992-2000 interferograms, with gray shaded zones indicating incoherent regions, where vegetation or erosion doesn't allow for interferometry. The Hayward fault is clearly visible as a step in the otherwise smoothly varying range-change field. This stacked data set is used in the inversion for aseismic fault slip rates on the Hayward fault, described below.
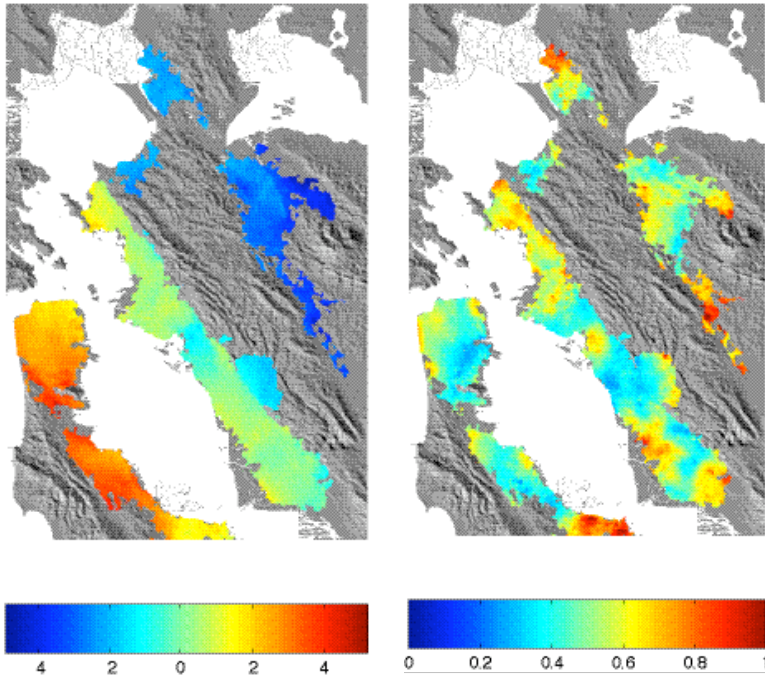
**Figure 2.** To the left, a stack of 8 differential interferograms of the San Francisco Bay Area shows the range change rate (in mm/yr) over a 7.5-year period. Superimposed over a shaded relief image is the change in range along the look direction of the satellite. Surface creep on the Hayward fault is represented by a discontinous jump in phase observed in Pinole, Castro Valley, and Fremont. The Interseismic strain profile across the Bay Area related to distributed elastic deformation across the plate boundary is represented by the gradient from red to blue. The right panel shows the 1-sigma error estimate of the range-change rates determined from the data scatter (in mm/yr).

*East Bay Faults Point Slip Rate Measurements From Earthquake Recurrence.* We have completed our initial and computationally intensive search for characteristic sequences on the southern Hayward, Calaveras and Mission faults. Our search for repeaters revealed large numbers of highly similar and repeating events (coherency > 0.95) in the NCSN catalog distributed widely on all three faults. Using NCSN surface data the fractions of identifiable repeaters is about 10%, 15% and 25%, for the northern Hayward fault, southern Hayward/Mission fault and Calaveras fault segments respectively. The lower fractions are explainable in part by lower slip rates and higher magnitude thresholds, since under these conditions recurrence intervals may be longer than observation times. In our prototype analysis on the northern Hayward fault, we showed that sufficient information was available to resolve spatially varying features of slip using surface NCSN data but that monitoring of short-term temporal variations was not practical with the limited resolution of the surface data on such a slowly moving fault. To the southeast, on the faster moving Mission and Calaveras faults, we have found sufficient rates of quake repetition to allow us to use NCSN data for monitoring transients (Figure 3) as is currently being achieved on the faster slipping San Andreas fault to the West (Nadeau and McEvilly, 2004). Using NCSN arrival times, we have relocated seismicity using a double-difference earthquake relocation program (Figure 3) and are evaluating the more highly resolved spatial and temporal seismicity patterns in relation to surface and spaced based deformation estimates, to the spatial and temporal distribution of repeating earthquake sequences and to the post-seismic period following the 1984 Morgan Hill earthquake.

Our preliminary findings indicate that, as at Parkfield and on the creeping section of the San Andreas fault, the locations of repeating earthquake sequences are confined to the central portion of

seismicity within large fault zones. However, repeating earthquakes are not ubiquitous on all faults. Our search for characteristic quakes failed to identify any repeating sequences on the Calaveras fault just north of its juncture (Manaker et al., 2003) with the Mission fault trend between Fremont and San Jose (Figure 3A). Furthermore, along the Mission and southern Hayward fault, repeating sequences only appear in the shallow portion of the seismogenic zone (Figure 3A, depth section). On these segments, below about 5-6 km, characteristically repeating sequences are absent while background seismicity can clearly be seen. This suggests that the boundary separating the repeating and non-repeating regions often delineates the boundary between creeping and non-creeping (locked) fault behavior at depth.

Also of note in this regard is the lack of repeating earthquake activity on two splays of transient earthquake activity emanating from the Calaveras fault south of San Jose. High precision relocations show that these splays were active during the post-seismic period following the Morgan Hill (MH) earthquake of 1984, but in subsequent years these splays have become aseismic (Figure 3, map view, 84-92.5 and 92.5 to 2002). It is not yet clear if the lack of repeating sequences on these splays is due to a relatively minor amount of slip release on the faults after MH or to a fundamental instability in the strength properties of earthquake patches on these subsidiary faults. In addition to the structural features manifest by the relocations and repeating earthquake analyses, temporal variations are also clearly evident.

On the Calaveras fault during the period 1984-1992.5 repeat rates (and inferred slip rates at depth) are very high in comparison to repeat rates for sequences from 1992.5 to 2002 (Figure 3A). The NW sub-segment identified in Fig. 3A is ~11 km long and at its southeast end is ~6 km away from the epicenter of MH. The MH event ruptured to the southeast of its epicenter, and there is no indication of accelerated deep creep in the NW subsegment. However, in the year prior to the LP quake, a significant acceleration in deep creep is observed. The SE sub-segment is ~6 km long and is adjacent to the MH epicenter. There is a strong acceleration in deep creep associated with MH on this segment, particularly in the first year following the event. The rate of creep decays approximately exponentially and by early 1996 has dropped to ~0. There is no evidence of slip acceleration prior to LP on this segment. On the sub-segment further to the southeast in Figure 3 (time series not shown) acceleration following MH is even stronger, and as of early 2001 deep creep rates show continued exponential decay. We are now investigating the spatio-temporal details of the response of the Calaveras fault to the 1984 Morgan Hill and 1989 Loma Prieta earthquakes.
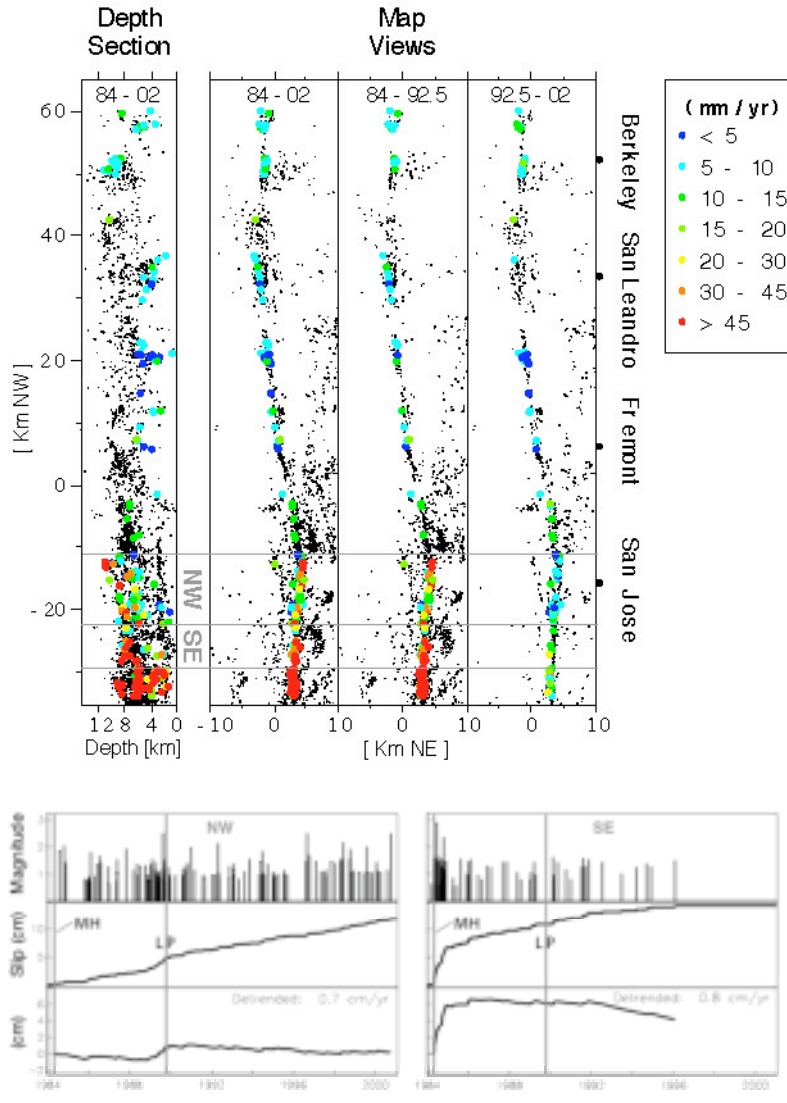
**Figure 3. (A)** Point fault slip rate estimates at depth inferred from recurrence intervals of characteristic micro-earthquakes, shown with the Hypo-DD relocated seismicity along a 120-km-long stretch of the East Bay area faults. Rates of slip in mm/yr are coded by color as indicated. Each color point represents the average slip rate between time sequential pairs of characteristic events in a sequence. Left panel shows, in depth section, all slip rate pair estimates and background seismicity for the time period 1984-2002. The remaining panels show in map view data for 1984-2002, 1984 to 1992.5, and 1992.5 to 2002.2. **(B)** Time series of magnitudes (top), cumulative deep slip (middle) and detrended cumulative slip (bottom) from characteristic microearthquakes occurring on the NW and SE sub-segments shown in (A). Vertical gray lines correspond to times of the Loma Prieta (LP) and Morgan Hill (MH) earthquakes.

Aseismic Slip Distribution Along the Hayward Fault. The Hayward fault is modeled as sub-vertical dislocations in an elastic half-space using the boundary element code POLY3D developed at Stanford University. The formulation for an angular dislocation allows for a more complex geometry than the commonly used rectangular dislocation (Okada, 1985). Surface creep rates and creep rates determined from characteristic repeating microearthquake sequences are used as additional constraints in the inversion. The deformation rate is assumed to be constant over the time spanned by the various data sets since no significant fault transients are known to have occurred on the northern and central Hayward fault during the time period of interest. Only the southern most few kilometers of the Hayward fault (km 63-68) exhibit transient behavior, which appears to be related to the stress perturbation and recovery imposed by the 1989 Loma Prieta earthquake (Lienkaemper et al., 1997; Lienkaemper et al., 2001). A weighted inversion is performed using a bounded variable least squares (BVLS) approach, which minimizes the L2 norm. Given the diversity in data used in this analysis, it is also useful to apply a factor that weights the data sets

relative to one another. A smoothing constraint is imposed using the Laplacian smoothing operator. The Hayward fault is represented by an 80-km-long by 12-km-deep fault plane discretized into 283 triangular subfaults with an average dimension of 3 km. The Hayward fault is meshed in this way in order to accommodate the divergence of the microseismicity at depth from the mapped surface trace as well as to incorporate subsurface salients, which may affect the near-fault data. Additional model parameters include four deep, vertical dislocations located beneath the San Andreas, Hayward, Calaveras, and Greenville faults. The deep dislocations accommodate the regional strain gradient across the plate boundary. The BVLS approach allows for the right-lateral slip rate to be bound within a range consistent with geologic estimates. Subfaults on the Hayward fault are bound between 0 and 12 mm/yr, which incorporates the inferred geologic rate of 9 mm/yr plus 3 mm/yr of error (Lienkaemper et al., 1991). Each deep dislocation is bound between 0 and 30 mm/yr. Preliminary results suggest that the distribution of aseismic slip-rate on the Hayward fault indicates spatially variable fault behavior consistent with the findings of previous studies (Figure 4) (Lienkaemper et al., 1991; Simpson et al., 2001). Slip-rates <1 mm/yr likely represents regions where the fault is not slipping either because the fault is locked or because slip is restrained. Locked sections may represent the nucleation site or the rupture area of future large earthquakes. The <1 mm/yr region below Oakland and at depth on the southern Hayward fault (km 20-35) agree with findings by Simpson et al. (2001) and Waldhauser and Ellsworth (2002, asperities B and C in Figure 10).
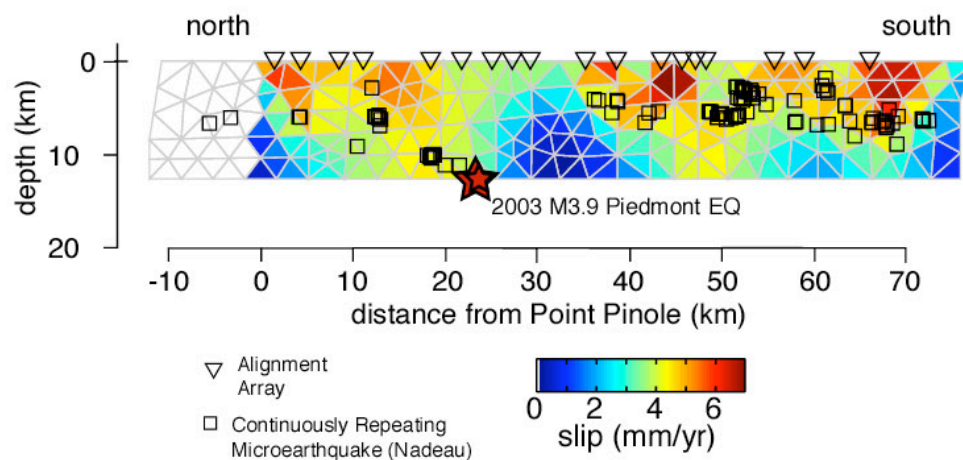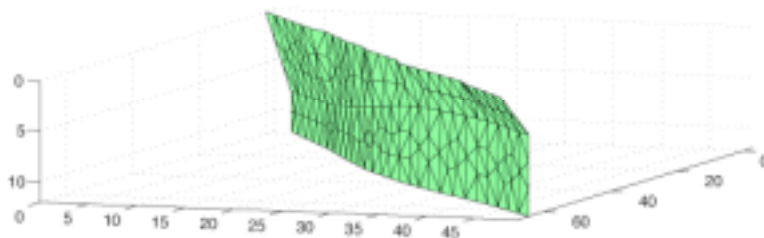


Figure 4. Top. Distribution of aseismic slip rates in mm/yr along the Hayward fault determined from GPS, InSAR, surface creep, and subsurface micro-earthquake repeater data (Schmidt, 2002).
Right. 3D geometry of the boundary element mesh of triangular elements used to represent the dipping geometry of the Hayward fault.

# HAYWARD, CALAVERAS, AND MISSION FAULT SUBSURFACE SLIP FROM JOINT ANALYSIS OF MICROEARTHQUAKE RECURRENCE AND SPACE GEODESY

**Roland Bürgmann**, University of California, Berkeley
Department of Earth and Planetary Science
307 McCone Hall
Berkeley, CA 94720-4767
Telephone: (510) 643-9545; FAX (510) 643-9980; burgmann@seismo.berkeley.edu
URL:http://www.seismo.berkeley.edu/~burgmann

## Non-Technical Summary

The earthquake cycle involves the accumulation of strain along locked faults followed by the catastrophic release of strain during an earthquake. The Hayward and Calaveras faults relieve strain in large earthquakes, but also by steady slip known as aseismic creep. The fundamental questions we investigate are where and how fast is strain being released by creep? We combine surveys of crustal deformation using space based geodetic techniques such as GPS and InSAR with traditional survey techniques to quantify surface deformation from locked and creeping faults. Using additional information from characteristically repeating microearthquakes and computer models, we determine the distribution and rate of creep at depth on the East Bay faults. These detailed maps of locked and creeping fault patches will improve our estimates of seismic potential and hazard along major faults in the San Francisco Bay area.

## Reports Published

Bürgmann, R., Fielding, E., and Sukhatme, J., 1998, Slip along the Hayward fault, California, estimated from space-based synthetic aperture radar interferometry: Geology, v. 26, p. 559-562.

Bürgmann, R. Schmidt, D., Nadeau, R., d'Alessio, M., Fielding, E., Lawrence, S., Manaker, D., McEvilly, T., and Murray, M.H., 2000, Earthquake potential along the northern Hayward fault, California, *Science,* 289, 1178-1182.

Johnson, L.R. and R.M. Nadeau, Asperity Model of an Earthquake - Static Problem, Bull. Seismol. Soc. Amer., 92, 672-686, 2002.

Manaker, D.M., R. Bürgmann, W.H. Prescott, and J. Langbein, Distribution of interseismic slip rates and the potential for significant earthquakes on the Calaveras fault, central California, *J. Geophys. Res.*, *108* (B6), doi:10.1029/2002JB001749, 2003.

Manaker, D.M., A.J. Michael, and R. Bürgmann, Subsurface structure and mechanics of the Calaveras Hayward fault stepover from three-dimensional vp and seismicity, San Francisco Bay region, California, *Bull. Seism. Soc. Am.*, *in review*, 2004.

Nadeau, R.M., and T.V. McEvilly, Seismological studies at Parkfield V: Characteristic microearthquake sequences as fault-zone drilling targets, *Bull. Seism. Soc. Am.*, *87*, 1463-1472, 1997.

Nadeau, R.M., and T.V. McEvilly, Fault slip rates at depth from recurrence intervals of repeating microearthquakes, *Science*, *285* (5428), 718-721, 1999.

Nadeau, R.M., R.A. Uhrhammer and T.V. McEvilly, How Similar Are Repeating Earthquakes? , Seism. Res. Lett., 73, 216, 2002.

Rolandone, F., R. Bürgmann and R.M. Nadeau, Time-dependent Depth Distribution of Aftershocks: Implications for Fault Mechanics and Crustal Rheology, Seism. Res. Lett., 73, 229, 2002.

Schmidt, D.A., and R. Bürgmann, Transient tectonics of the Hayward, Calaveras, and Mission fault junction, *Eos Trans. AGU*, *82* (47), G22D-09, 2001.

Schmidt, D.A., R. Bürgmann, and S.A. Lawrence, Imaging time-dependent fault creep and basin subsidence in the San Francisco Bay Area using InSAR, *Eos Trans. AGU*, *81*, 336, 2000.

Schmidt, D.A., The kinematics of faults in the San Francisco Bay area inferred from geodetic and seismic data, Ph.D. thesis, University of California, Berkeley, 2002.

Schmidt, D.A., and R. Bürgmann, Time dependent land uplift and subsidence in the Santa Clara valley, California, from a large InSAR data set, *J. Geophys. Res.*, *submitted Oct. 2002*.

Templeton, D.C., R.M. Nadeau, and R. Bürgmann, Structure and kinematics at the juncture between the San Andreas and southern Calaveras faults, *Eos Trans. AGU*, *82* (47), S32E-02, 2001.

# References

Lienkaemper, J.J., G. Borchardt, and M. Lisowski, Historic creeprate and potential for seismic slip along the Hayward Fault, California, *J. Geophys. Res.*, *96*, 18261-18283, 1991.

Lienkaemper, J.J., J.S. Galehouse, and R.W. Simpson, Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake, *Geophys. Res. Lett.*, *28*, 2265-2268, 2001.

Okada, Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seism. Soc. Am.*, *75*, 1135-1154, 1985.

Simpson, R.W., J.J. Lienkaemper, and J.S. Galehouse, Variations in creep rate along the Hayward fault, California, interpreted as changes in depth of creep, *Geophys. Res. Lett.*, *28*, 2269-2272, 2001.

Waldhauser, F., and W.L. Ellsworth, Fault structure and mechanics of the Hayward fault, California, from double-difference earthquake locations, *J. Geophys. Res.*, *107*, 10.1029/2000JB000084, 2002.

Waldhauser, F., HypoDD – A Program to Compute Double-Difference Hypocenter Locations, *U.S. Geol. Surv. Open File Report* 01-113, 2001.

# Data Availability

Data from GPS campaigns are publicly available from the UNAVCO Campaign Data Holdings Archive. Both raw GPS data and accompanying metadata are included and freely accessible at http://archive.unavco.ucar.edu/cgi-bin/dmg/groups?cpn=1&oby=group_name

Data collected by our group for this project are archived under the Group Names of "Calaveras Fault", "Hayward Fault" and "Loma Prieta."

Please see http://www.unavco.ucar.edu/data_support/data/general.html for policies regarding the use of these freely available data. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

For more information regarding data availability, contact:

Dr. Roland Bürgmann

Department of Earth and Planetary Science, University of California, Berkeley

307 McCone Hall, Berkeley, CA 994720-4767

e-mail:burgmann@seismo.berkeley.edu

URL:http://www.seismo.berkeley.edu/~burgmann